Pergamon

Quaternary International, Vol. 21, pp. 113–119, 1994.

1040–6182/94 $26.00

1040–6182(93)E0009–F

THE MERA SITE REVISITED: ICE-AGE AMAZON IN THE LIGHT OF NEW EVIDENCE

K. Heine
Universität Regensburg, Institut für Geographie, 93040 Regensburg, Germany

The Mera site is the only fossil pollen and forest bed radiocarbon dated 33–26 ka BP in tropical lowland Amazonia. Here I conclude, from the study of the geology, geomorphology and paleopedology of the Mera site area, as well as from new ^{14}C and U/Th age determination of the organic layers, that the pollen sections are not of last glacial age but of Middle Pleistocene age, at least. No evidence of last glacial age has been found for the Mera fossil forest beds. The data from the Mera sites, therefore, should neither be used for climate reconstructions of the last glacial maximum, nor for disputing the refugial theories.

INTRODUCTION

There has been considerable debate about the magnitude of the decrease of temperature and the change in precipitation in the American tropics (Amazon Basin, tropical Andes) during the last glacial maximum. Reconstructions of the glacial climate are based on palynological and geological–geomorphological evidence. It is now generally agreed that equatorial South America has been subjected to major climatic change during the last glacial maximum (Prance and Lovejoy, 1984). Unfortunately, the paleoclimatic evidence from lowland Amazonia is without radiocarbon control to justify it. Only a single site from the western Amazon Basin near the Andean foothills was radiocarbon dated and the results suggest a descent of montane forest of more than 700 m at 33–26 ka BP, requiring a temperature depression of at least 4.5°C in the Amazon lowlands (Liu and Colinvaux, 1985; Colinvaux and Liu, 1987; Colinvaux 1987a, b, 1989a, b; Colinvaux *et al.*, 1988; Bush *et al.*, 1990). According to Bush *et al.* (1990), the temperature depression experienced in Amazonia during the LGM (last glacial maximum, ca. 18 ka BP) should have been as cold as or even colder than the 7.5°C cooling that the authors document by fossil pollen and forest bed studies from Mera, Ecuador. This temperature depression ties in with observations from the tropical Andes in Colombia (Hooghiemstra, 1989; Helmens, 1988; Schubert and Clapperton, 1990), in Ecuador (Clapperton, 1990) and in Perú (Rodbell *et al.*, 1991). The Mera site is the only radiocarbon dated evidence from the last glaciation in Amazonia itself, where pollen and megafossil data were studied in detail (Liu and Colinvaux, 1985; Colinvaux, 1987b; Bush *et al.*, 1990). The Mera record was introduced into the literature as a last glacial age site in the Amazon. The Mera site data are used as reference data by many authors (e.g. Salo, 1987; van der Hammen *et al.*, 1992a; Lautenschlager, 1991; Hoppe, 1990; Colinvaux, 1987a), although they are incompatible with the marine temperature record (CLIMAP Project Members, 1976, 1981) and model simulations (Rind and Peteet, 1985; Lautenschläger, 1991). Because of the great importance of the results on ice-age climatic conditions in Amazonia made available by Liu and Colinvaux (1985), Colinvaux and Liu (1987) and Bush *et al.* (1990), I visited the Mera site in 1990 and again in 1991 to study the morphology, sedimentology and paleopedology of the section (Figs 1, 2 and 3).

THE MERA SITE, ECUADOR

The description of the Mera sections by Liu and Colinvaux (1985) introduced these first radiocarbon dated pollen and megafossil layers into the dispute on Amazonian last glacial maximum climate reconstructions. The Mera site itself and paleoecological data were presented by Liu and Colinvaux (1985). From this publication, the following characterization of the Pleistocene site is adopted:

"The forest beds are exposed along the road cuts at two sites near Mera (1°28'S, 78°6'W, elevation 1,100 m) in Oriente Province, Ecuador (Fig. 1). The area has a mean annual temperature of 20.8°C and precipitation of > 4,800 mm, making it one of the wettest places in the Amazon Basin. . . . At the first exposure, an organic bed ~2 m thick is overlain by ~12 m of largely inorganic deposit . . . suggesting lahars . . . A darker lithological unit, possible organic, overlies the upper debris flow and is in turn overlain by a fluvial sequence of clast-supported gravel and sand . . . Wood sample 5 yielded a radiocarbon date of 33,520 ± 1,010 yr B.P. (B-9618).

The second exposure lies about 3 km east of the first. The road-cut section is ~20 m high here and consists of deeply weathered fluvial sand at the base, overlain unconformably by a clast-supported gravel with rounded boulders. The forest-bed, ~2 m thick, lies above the gravel and is overlain by fluvial sand . . . Wood samples . . . were taken from the slumped blocks. Sample 4 has a radiocarbon age of 26,530 ± 270 yr B.P. (B-10170) . . .

Wood samples from both forest beds . . . are of *Podocarpus* . . . *Podocarpus* typically grows today in the Andean forest between the 2,000- and 3,500-m contours in Ecuador . . . The lowest confirmed modern elevation (of *Podocarpus*) is 1,800 m. The late Pleistocene population of *Podocarpus* grew at least 700 m below the

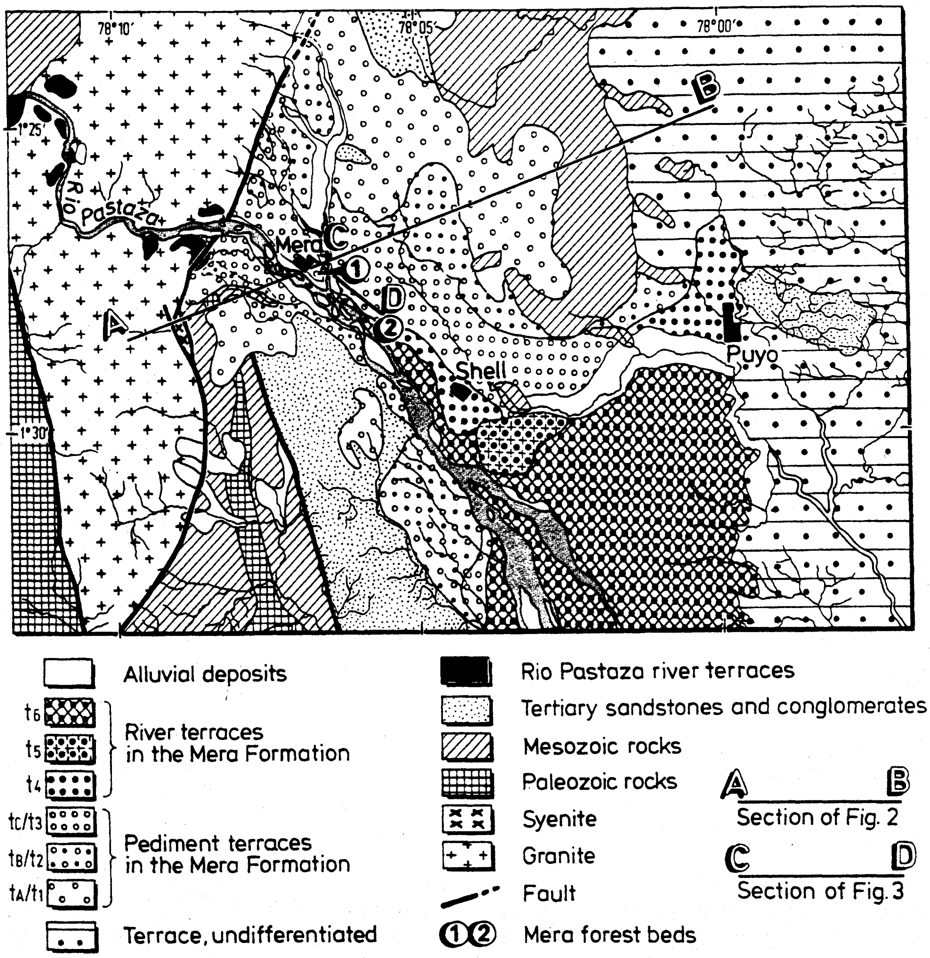

FIG. 1. The Quaternary geology of the Mera/Puyo region, Ecuador (after Mapa Geológico del Ecuador, Sheet 88—Baños, 1979 and Sheet 103—Puyo, 1979/80).

lowest modern populations. If . . . the altitudinal ranges are temperature dependent, we can calculate the necessary temperature depression. Assuming a lapse rate of 0.65°C per 100 m, the minimum lowering of mean annual temperature is 4.5°C. As the pollen data suggest extensive montane forests at this elevation, the actual lower limit of *Podocarpus* was certainly below 1,100 m and the actual temperature depression > 4.5°C . . . Note that both our radiocarbon dates fall within various definitions of a mid-Wisconsin interstade, suggesting that forest and temperature depressions at full glacial times were even larger than our calculations suggest".

In a more recent study, Bush *et al.* (1990) refer to the Mera site in a slightly different way; on the one hand, the geographic location is 1°28'S and the second Mera site is characterized as road-cut (Liu and Colinvaux, 1985) and, on the other hand, the location is 1°29'S and the second Mera site should be a Río Pastaza cliff (Bush *et al.*, 1990). Furthermore, Bush *et al.* (1990) give a second radiocarbon date for the Mera pollen section; unfortunately they do not mention the laboratory number of the ^{14}C dating. In their paleoclimate interpretation of the Mera sections, Bush *et al.* (1990) believe in the reliability of the ^{14}C dates in a very strict way. They elaborate a paleoclimate for different temporal phases, such as 33–30 ka BP and 30–26 ka BP with regard to the ^{14}C dates.

"We conclude, therefore, that the observed vegetation changes at our two study sites (Mera and San Juan Bosco) were the product of a regional cooling, suggesting a 7.5°C temperature depression at low altitudes near 0° latitude during the period 33,000 to 30,000 yr B.P. . . . The lowermost date from Mera, taken from a large single piece of wood, gives an effective minimum date for the onset of this cold period of 33,520 ± 1010 yr B.P. (B-9618). . . . The data from Mera and San Juan Bosco suggest the period 30,000 to 26,000 yr B.P. to have been one of warming . . ." (Bush *et al.*, 1990, p. 342).

Geological and Geomorphological Setting

About 4 km northwest of the Mera 1 section, the Río Pastaza leaves the Andean mountain ranges, from which emerge debris-laden rivers (Río Pastaza, Río Chico, Río Alpayacu) (Fig. 1). Large alluvial fans have been built of gravels, debris and sand by flood waters of these south-flowing rivers. By lateral planation, pediment-like forms developed (Heine, 1991). After the formation of the upper pediment, the streams cut down through their pediment deposit and eventually sweep most of it out of the region. During this degradation a terrace sequence is formed that is now disected by many small rivers. The formation of the pediment gravels suggests a relatively arid climate during the deposition. Such paleoenvironmental conditions may have occurred during the Late Pliocene or Early Pleistocene

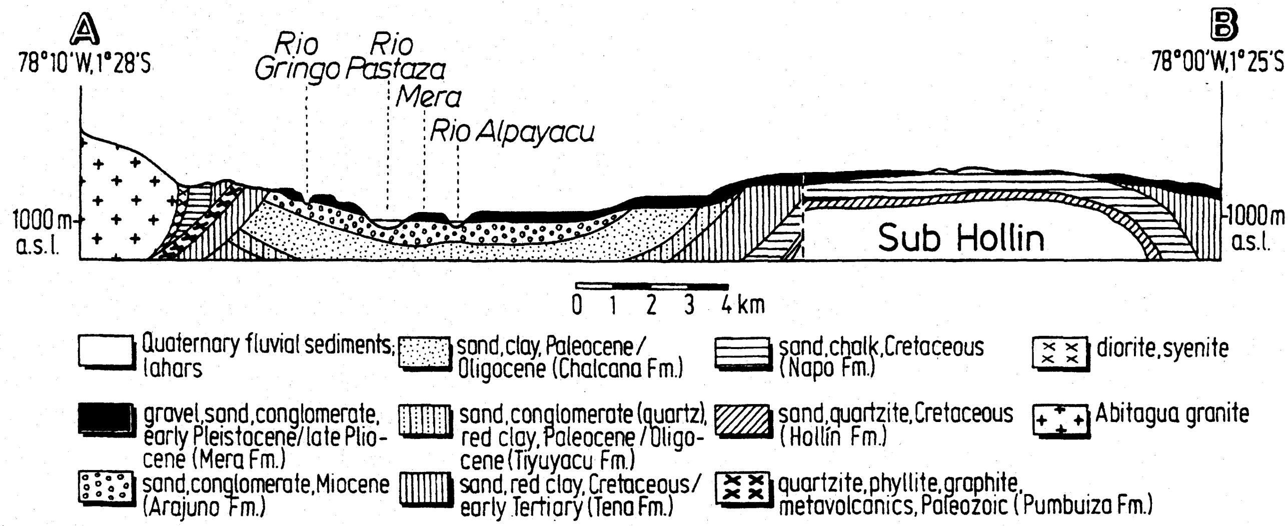

FIG. 2. Geological section of the Mera area (after Mapa Geológico del Ecuador, Sheet 88 — Baños, 1979).

(see Klammer, 1984). With the shifting of Quaternary climatic conditions, the development of a series of alluvial river terraces started. In the vicinity of the Mera 1 section, a wide terrace sequence is formed by the degradation of the lower pediment gravels (see also Räsänen *et al.*, 1990).

According to the geomorphic features, the age of the pediment gravels from the Mera 1 section is of Late Pliocene–Early Pleistocene times. This is corroborated by geological investigations (Mapa Geológico del Ecuador, Hoja 88 — Baños, 1979; Hoja 103 — Puyo, 1979/80).

The paleosols that developed on the pediment surfaces of the older pediments mostly show strongly red colored ferralic Arenosols, ferric Acrisols and xanthic Ferralsols (see Sombroek, 1984). These ferrallitic soils represent the final phase of development and weathering of soils in a hot and humid tropical climate. Soils comparable to these relict ferrallitic soils do not develop today in the vicinity of the Mera site nor did they develop during the Holocene. Even during the late Quaternary, their formation was absent in comparable areas of the eastern Amazon Basin.

Both the morphology (pediments and river terraces) and the paleosols (type and weathering thickness of the relict ferrallitic soils; see Semmel, 1985) suggest that the sediment sequences with the organic layers of the Mera sections were not deposited during the last glacial (33.5–26.5 ka BP), as is concluded by Liu and Colinvaux (1985) and Bush *et al.* (1990), as well as by Colinvaux (1987a, b, 1989a, b).

The Mera 1 Section

The Mera 1 section (Figs 1 and 3) of Liu and Colinvaux (1985) is situated near the Río Pastaza/Río Alpayacu confluence. The organic layer studied by Liu and Colinvaux (1985) and Bush *et al.* (1990) is underlain and overlain by lahar deposits. Another organic layer is found in the upper part of the section on top of the lahar sediments. So, at least

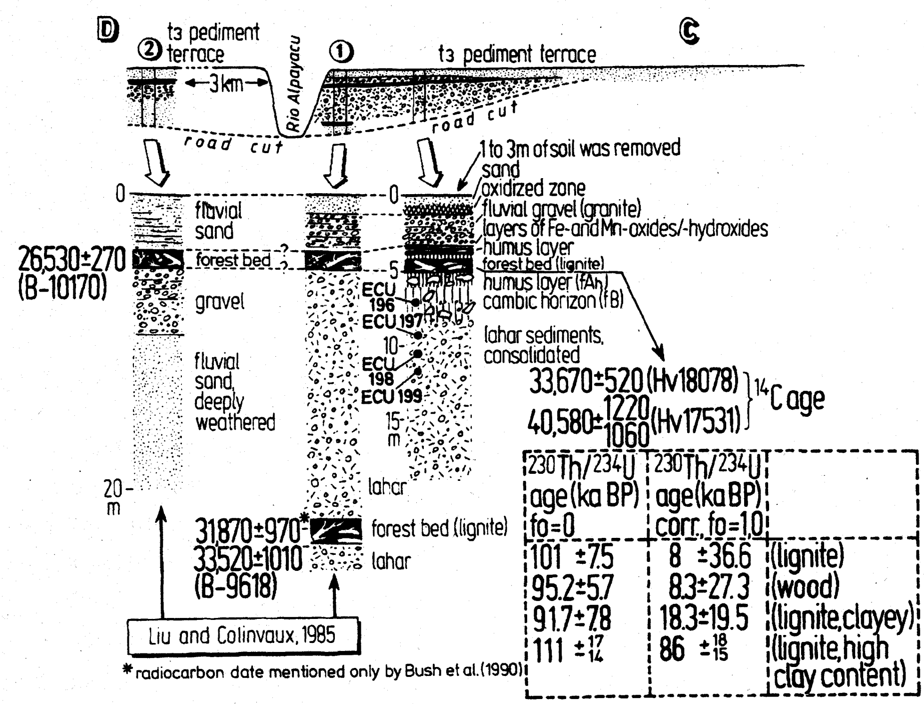

FIG. 3. The Mera sections. For location of the sites, see Fig. 1.

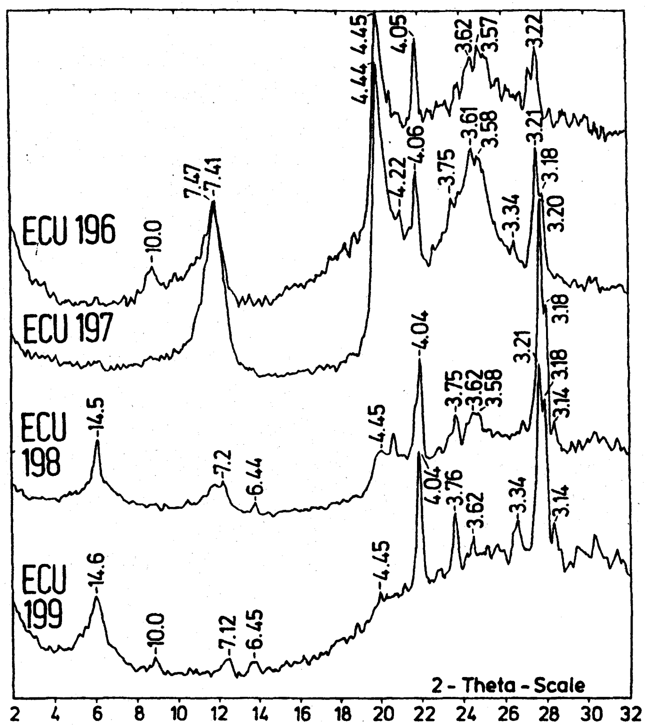

FIG. 4. XRD analysis of the samples ECU 196–199, fraction < 2 μm, Mg-treated, Cu-*k*α radiation, all peak positions in Å units.

two different lahar events are documented by the sequence. According to the geomorphological–geological and paleopedological findings during my first visit in 1990 (Heine, 1991), it was assumed that the basal organic layer dated to 33.5 ka BP by Liu and Colinvaux (1985) was beyond the radiocarbon time scale. If any, only the upper organic layer of the sequence could be of last glacial times. So, in 1991 the investigations were concentrated on the upper organic layer.

The lahar contains mainly gabbrodiotite and documents an effusive volcanic activity. The material is light-colored and consolidated. In the upper parts, the lahar is rich in clay and light blue in color. On top, the lahar is of intensive black to brown color and rich in clay and organic material. The mineral components of the lahar are plagioclase (= bytownite, ca. 80%), pyroxene (= enstatite, ca. 15%) and opaque iron ore (= magnetite and ilmenite, ca. 5%); biotite and hornblende are rare. The fabric shows typical

TABLE 1. Geochemistry of the lahar (wt %); the location of the samples is shown in Fig. 3

	ECU 196	ECU 197	ECU 198	ECU 199
SiO_2	42.09	52.55	59.03	55.46
Al_2O_3	31.02	28.84	19.06	16.77
Fe_2O_3	1.5	2.15	6.77	6.31
TiO_2	1.65	1.44	0.87	0.76
MgO	0.23	0.65	2.66	3.04
CaO	0.63	1.98	5.40	6.00
Na_2O	0.57	1.88	3.60	3.65
K_2O	0.47	0.92	1.42	1.45
P_2O_5	0.19	0.23	0.23	0.22
SUM	78.00	90.64	99.04	93.66
GV	22.4	10.3	2.1	6.5
Mol $\frac{SiO_2}{Al_2O_3}$	2.3	3.1	5.3	5.6

characteristics produced by flowage. For the geochemistry, see Table 1. The upper part of the lahar is deeply weathered. According to mineralogical, pedological and geochemical investigations a hydromorphic soil developed. The clay mineral assemblages of the samples ECU 196 and 197 differ very much from those of samples ECU 198 and 199 (Fig. 4). Halloysite is the dominant clay mineral of the weathered material; in addition, feldspar and quartz peaks can be seen in the X-ray diagrams. The clay mineral halloysite could not be recognized in many soil profiles of the Amazonian lowlands (Irion, 1984). In Amazonia, good drainage normally leads to kaolinite weathering profiles, whereas bad drainage favors formation of montmorillonite (Irion, 1984). We assume that in the Mera section the influence of the parent rocks (= gabbrodiorite) leads to the formation of halloysite-rich clay horizons in the fossil hydromorphic soil. The distribution of SiO_2 and Al_2O_3 and their moleratios (Table 1) of the samples ECU 196–199 also document the intense weathering. Al_2O_3 is enriched in the upper part of the decomposed lahar, whereas Fe_2O_3 decreases. These parts of the lahar deposits contain fragments of tree trunks, big roots and branches, thus documenting that the wood pieces were transported down-valley with the lahar material. The interbedded wood fragments are relatively fresh, although the chemical composition of the lahar sediments and the formation of halloysite leads to the conclusion that a relatively long and intensive influence of weathering processes had taken place. A layer of black lignite with many stubs, trunks and branches of trees is on top of the lahar and is in turn overlain by brown clays that document sedimentation of alluvial clays after the formation of the organic material. The upper part of the clay layer is black and humus. It serves as an unpenetrable layer for the seepage water, thus leading to oxidation of iron in the lowermost parts of the overlying fluvial gravels. The gravels consist exclusively of granites that originate from the Jurassic–Cretaceous Abitagua Granite in the northwest of the section. These gravels are attributed to the Río Alpayacu drainage system; they are more or less unweathered. Sandy material with iron bands and a humus layer on top conclude the section.

Two samples of the lignite layer were ^{14}C dated (Table 2): a sample rich in wooden material yielded an age of 40,580 + 1220/–1060 BP (Hv 17,531) and a sample of clayey lignite yielded an age of 33,670 ± 520 BP (Hv 18,078). The ^{14}C dates show that there is no consistency in the dates and they do not make any sense in connection with the ^{14}C dates reported by Liu and Colinvaux (1985) and Bush *et al.* (1990) (see Fig. 3). Furthermore, a set of samples were collected for U/Th age determinations (see Table 3). The applicability of the U/Th dating method for lignite and peat will not be discussed here (see e.g. Van der Wijk *et al.*, 1986; Vogel and Kronfeld, 1980). If the U/Th method is applied here, the main object is to yield further information on the minimum age of the Mera 1 section. Four samples were collected at different places within the organic layer. Sample ECU 192 consists of lignite more or less without clay; sample ECU 193 is a piece of wood; sample ECU 195 is lignite with a moderate clay content; sample ECU 194 is lignite with a high clay content. The U/Th dating results show that an open

TABLE 2. Radiocarbon ages of the Mera sites

Lab. no., Hv	Sample ECU	Material	$\delta^{13}C$ (‰)	Conventional ^{14}C age (years before 1950)
18, 078	195	lignite	–29.1	33,670 ± 520
17, 531	127	wood	–27.9	40,580 + 1220/ –1060

system was present and that there was a penetration of environmental uranium and/or thorium after deposition of the organic material. In the extremely humid climate near Mera, the penetration of seepage water is quite common to all near-surface sediments. We assume that this penetration of seepage water was prevented to a certain degree by clayey lenses and clay layers within the lignite sequence. Furthermore, the presence of clay in the samples can be used for detrital corrections (see Geyh and Schleicher, 1990). The samples contain detrital material of different origin. Using a correction factor of 1.0 yields Holocene ages of the samples, with the exception of ECU 194. The uranium content of the samples decrease with increasing clay content, showing that the material with low or no clay was enriched to a higher degree with uranium by seepage water. Therefore, a relationship between U/Th ages and clay content of the material can be seen. Though the results give limited evidence of the U/Th ages of the lignite layer, we believe that the U/Th dates, together with the finite ^{14}C dates, prove an age of the lignite of > 51 ka BP, at least (Geyh, M.A., *pers. commun.*, 1992). Thus, the results tie in with the geological–geomorphological and paleopedological observations and strongly suggest an age older than the last glacial.

DISCUSSION

There is strong evidence that the radiocarbon dates mentioned by Liu and Colinvaux (1985) and Bush *et al.* (1990) do not represent the true ages of the deposition of the organic layers at the Mera sections. The fact that the radiocarbon dates of the lignites beneath and on top of the youngest lahar deposits show the same range of ^{14}C dates, namely 33,670 ± 520 BP (Hv 18,078), and an older finite age of 40,580 ± 1220/–1060 BP (Hv 17,531) for the upper organic bed and 33,520 ± 1010 BP (B-9618) and 31,870 ± 970 BP (lab. no. unknown) for the older, lower lignite, documents the unreliability of the radiocarbon ages not only of the upper organic layer but also of the basal peat layer. Taking into account that the basal organic layer studied by Liu and Colinvaux (1985) and Bush *et al.* (1990) is overlain by ~12 m of lahar deposits that are deeply weathered, then it becomes evident that the radiocarbon ages cannot contribute to establish a late glacial chronology. All ^{14}C dates of the Mera sections are finite in age, thus showing quite clearly the contamination of the organic layers by seepage water in an open system. The range of the ^{14}C dates between ca. 33.5 and 26.5 ka BP is quite common for contaminated material of much older age (see also Räsänen *et al.*, 1990). This is corroborated by the U/Th dating results. Furthermore, the organic layers stem from sections that are apparently of pre-late Quaternary age, as shown by the geological and geomorphological setting, as well as by the paleopedological evidence.

Some inconsistencies in the descriptions of Liu and Colinvaux (1985) and Bush *et al.* (1990) point to differing interpretations of the facts. To explain the changes in topography indicated by different fluvial depositional systems, Bush *et al.* (1990, p. 336) assume local tectonic activity; this local tectonism is believed to explain the apparent contemporaneity proved by the radiocarbon dates of the Mera sites with the San Juan Bosco sites, which are found about 190 km south of Mera. I cannot agree with this explanation, because of the deep weathering of the fluvial sediments, lahars and pediment gravels, and sands. The stream down-cutting is not restricted to the late Quaternary, as assumed by Colinvaux and co-workers; on the contrary, the down-cutting is an indispensable condition for the formation of the soils without the influence of groundwater, as indicated by the fossil soils of the Mera sites and of adjacent pediment terraces.

Melastomataceae and *Hedyosmum* are represented with high percentages in the pollen diagrams, but are sparse in surface samples of the modern analog sites from Ecuador. *Podocarpus*, too, never attains values greater than 1% in modern samples, even in modern Andean forests in which the genus is an important element (Bush *et al.*, 1990), whereas *Podocarpus* pollen in the upper section of the Mera record attains values in excess of 5%, 10 times the representation found in any of the analog sites. I suggest that the pollen assemblages of the Mera section do not represent the last glacial period but an earlier Quaternary habitat.

For other parts of western Amazonia we have very little published data of late Quaternary radiocarbon dated sequences. In Colombian Amazonia, organic material from fluvial sediments, in low terrace sediments up to ca. 8 m above low water level of the middle Caquetá River, was

TABLE 3. U/Th ages of the Mera sites

Lab. no., Uh Hv	Sample ECU	^{238}U (ppm)	^{232}Th (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}Th$	$^{230}Th/^{234}U$ age (ka BP) $fo = 0$	$^{230}Th/^{234}U$ age (ka BP) corr., $fo = 1.0$	Material
853	192	2.081	4.066	1.005	0.9	0.605	101	8	lignite, without clay
18,078		± 0.029	± 0.177	± 0.008	± 0.0	± 0.026	± 7.5	± 36.6	
854	193	1.474	2.735	0.996	0.9	0.584	95.2	8.3	wood
18,078		± 0.019	± 0.099	± 0.007	± 0.0	± 0.021	± 5.7	± 27.3	(*Podocarpus*?)
856	195	1.939	2.878	0.993	1.2	0.570	91.7	18.3	lignite, moderate
18,078		± 0.025	± 0.158	± 0.007	± 0.1	± 0.030	± 7.8	± 19.5	clay content
855	194	0.244	0.166	1.053	3.0	0.645	111	86	lignite, high
18,078		± 0.006	± 0.027	± 0.032	± 0.5	± 0.048	– 14 + 17	– 15 + 18	clay content

dated between 56 and 30ka BP (van der Hammen *et al.*, 1992a). From Perú, fluvial sediments of the 'tierra firme' yield ^{14}C dates of ca. 36.5 ka BP (Räsänen *et al.*, 1987; Campbell and Pittmann, 1989). These dates, together with those published by Räsänen *et al.* (1990) and by Liu and Colinvaux (1985), cause van der Hammen *et al.* (1992a) to argue for a low fluvial terrace of Middle Pleniglacial age over a wide area of western Amazonia. The Mera sections do not represent fluvial low terrace systems, nor do they represent sediments of Middle Pleniglacial age. The dated low terrace systems of the Caquetá River in Colombia and of the Peruvian Amazonia, on the other hand, give convincing evidence that the organic layers of the Mera sections must be of a greater age than assumed by Colinvaux and co-workers. The Mera sections occur in the upper part of pediment sequences, that are definitely older in age than the fluvial terraces. This is supported by the evolution of the Plio–Pleistocene fluvial landscape in the western Peruvian Amazon (Räsänen *et al.*, 1990), where late Tertiary alluvium and younger alluvial terraces and plains build up the *tierra firme*. Thermoluminescence and ^{14}C dating show local aggradation of the younger alluvium (low terrace) between 180 and 30 ka and by this document that the tierra firme must be of greater ages (Räsänen *et al.*, 1990; Ervanne *et al.*, 1992).

Unfortunately, no data on the late glacial temperature depression of the Amazonian lowland exist. Some authors suggest a slightly drier climate compared with today (e.g. van der Hammen *et al.*, 1992a, b; Vaz and García-Miragaya, 1992), but they give no information about the late glacial cooling. The view of Bush *et al.* (1990, p. 343) that further climatic reconstructions modeling the temperature of the lowland American tropics should incorporate a probable cooling of ca. 7–8°C cannot be confirmed according to the reinterpretation of the Mera sites, as well as the examination of published data.

The ice-age climate simulation of lowland Amazonia (Lautenschlager, 1991) shows a temperature reduction of 2.0°C in January and 2.4°C in July. According to the Clausius–Clapeyron equation, a tropical lowland temperature reduction of 2°C, the annual mean reduction for the Amazon and the Kongo Basins are simulated by the T21 model, results in an evaporation decrease of 20–30%. The precipitation reduction in the Amazon Basin was 5% in July and 10% in January (Lautenschlager, 1991). The palynological evidence of Liu and Colinvaux (1985) and Bush *et al.* (1990) does not fit the simulated reduction range of the T21 version of the Atmospheric General Circulation Model (Lautenschlager, 1991). Although in tropical lowland areas the last glacial temperature depression is disputed, most geological–palynological evidence shows apparent temperature reductions that represent values far too high. Bonnefille *et al.* (1990) proved a temperature reduction for Burundi, East Africa of 4 ± 2°C according to quantitative estimates of temperature and precipitation using a multivariate analysis of pollen time-series data from peat deposits for the past 40,000 years. These lower estimates from a site of intermediate elevation in East Africa may help resolve the differences between the simulated and observed records (Bonnefille *et al.*, 1990). It seems that the model simulations of tropical lowland temperatures at the last glacial maximum are more reliable than the estimates of lowland temperatures from snow-line and tree-line reconstructions. The ice-age climate simulation using CLIMAP sea-surface temperatures does not provide sufficient cooling at low latitude locations to match the terrestrial snow-line and pollen data (Rind and Peteet, 1985). One can assume that the models cannot resolve small-scale effects in mountain regions; to isolate mountain effects, additional modeling studies should use as fine a resolution as is practical (Rind and Peteet, 1985; Lautenschlager, 1991).

Therefore, at present, we first have to question the reliability of the interpretation of snow-line and pollen data from tropical mountains with respect to the tropical lowland climate (see Rodbell, 1992; Seltzer, 1990, 1992); only subsequently should we think of great errors in the data set of the CLIMAP or other reconstructions (e.g. Jianning Le, 1992).

CONCLUSIONS

No evidence of the last glacial age has been found for the Mera fossil forest beds and pollen assemblages that are reported to be of the last glacial age and to give evidence of relatively cold temperatures, even in Amazonian lowlands during the last ice-age. The Mera forest beds seem to be of at least Middle Pleistocene age according to the geomorphological and paleopedological setting. According to ^{14}C in combination with U/Th age determinations, the age of the organic layers near Mera are evidently older than ca. 50 ka BP. Compared with dated fluvial terrace sequences from the Caquetà River in Colombia and from Peruvian Amazonia, the Mera sites are also of Middle Pleistocene age, at least.

ACKNOWLEDGEMENTS

The research was supported by grants of the Deutsche Forschungsgemeinschaft. I thank M.A. Geyh (Hannover) for radiocarbon and U/Th age determinations, J. Völkel (Regensburg) for soil sample analyses, A. Forster (Regensburg) for geochemical and mineralogical investigations, A., J., H. and C. Heine for field assistance, as well as many people in Ecuador who helped during my studies.

REFERENCES

Bonnefille, R., Roeland, J.C. and Guiot, J. (1990). Temperature and rainfall estimates for the past 40,000 years in equatorial Africa. *Nature*, **346**, 347–349.

Bush, M.B., Colinvaux, P.A., Wiemann, M.C., Piperno, D.R. and Liu, K.-B. (1990). Late Pleistocene temperature depression and vegetation change in Ecuadorian Amazonia. *Quaternary Research*, **34**, 330–345.

Campbell, K.E. and Pittman, L.R. (1989). The Quaternary geology of Departamento de Madre de Dios, Perú. *In*: *Congreso Peruano de Geología*, 6, Lima. Proceedings Lima, Sociedad Geológica del Perú.

Clapperton, C.M. (1990). Glacial and volcanic geomorphology of the Chimborazo-Carihuairazo Massif, Ecuadorian Andes. *Transactions of the Royal Society, Edinburgh (Earth Sciences)*, **81**, 91–116.

CLIMAP Project Members (1976). The surface of the ice-age Earth. *Science*, **191**, 1131–1137.

CLIMAP Project Members (1981). Seasonal reconstructions of the Earth's Surface at the Last Glacial Maximum. Geol. Soc. Am. Map and Chart Series MC 36.

Colinvaux, P.A. (1987a). Environmental history of the Amazon Basin. *Quaternary of South America and Antarctic Peninsula*, **5**, 223–237.

Colinvaux, P.A. (1987b). Amazon diversity in light of the paleoecological record. *Quaternary Science Reviews*, **6**, 93–114.

Colinvaux, P.A. (1989a). Der Amazonas-Regenwald. *Spektrum der Wissenschaft*, **1989**, 70–76.
Colinvaux, P.A. (1989b). Ice-age Amazon revisited. *Nature*, **340**, 188–189.
Colinvaux, P.A. and Liu, K.-b. (1987). The late-Quaternary climate of the western Amazon Basin. *In*: Berger, W.H. and Labeyrie, L.D. (eds), *Abrupt Climatic Change*, pp. 113–122. Reidel, Dordrecht.
Colinvaux, P.A., Olson, K. and Liu, K.-b. (1988). Late-glacial and Holocene pollen diagrams from two endorheic lakes of the inter-Andean Plateau of Ecuador. *Reviews of Paleobotany and Palynology*, **55**, 83–99.
Ervanne, H., Jungner, H. and Räsänen, M. (1992). Dating of fluvial sediments from the Amazon lowland in Peru. *Quaternary Science Reviews*, **11**, 71–73.
Geyh, M.A. and Schleicher H. (1990). *Absolute Age Determination. Physical and Chemical Dating Methods and Their Application.* Springer, Berlin, 503 pp.
Heine, K. (1991). Critical comments on ice-age Amazon history of climate and vegetation based on new field evidence. *Bamberger Geograph. Schr.*, **11**, 337–349.
Helmens, K.F. (1988). Late Pleistocene glacial, sequence in the area of the high plain of Bogotá. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **67**, 263–283.
Hooghiemstra, H. (1989). Quaternary and Upper Pliocene glaciations and forest development in the tropical Andes: evidence from a long high-resolution pollen record from the sedimentary Basin of Bogotá, Colombia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **72**, 11–26.
Hoppe, A. (1990). Ist El Dorado gefunden? Geologie und Bodenschätze Amazoniens. *Ber. Naturf. Ges. Freiburg i. Br.*, **80**, 19–58.
Irion, G. (1984). Clay minerals of Amazonian soils. *In*: Sioli, H. (ed.), *The Amazon. Limnology and Landscape Ecology of a Mighty Tropical River and its Basin*, pp. 537–579. W. Junk, Dordrecht.
Jianning Le (1992). Palaeotemperature estimation methods: Sensitivity test on two western equatorial Pacific cores. *Quaternary Science Reviews*, **11**, 801–820.
Klammer, G. (1984). The relief of the extra-Andean Amazon basin. *In*: Sioli, H. (ed.), *The Amazon. Limnology and Landscape Ecology of a Mighty Tropical River and its Basin*, pp. 47–83. W. Junk, Dordrecht.
Lautenschlager, M. (1991). Simulation of the ice age atmosphere—January and July means. *Geol. Rundschau*, **80**, 513–534.
Liu, K.-b. and Colinvaux, P.A. (1985). Forest changes in the Amazon Basin during the last glacial maximum. *Nature*, **318**, 556–557.
Mapa Geológico del Ecuador, Hoja 88-Baños, 1979; Hoja 103-Puyo, 1979/80. Quito.
Prance, G.T. and Lovejoy, T.E. (eds) (1984). *Amazonia*. Pergamon, Oxford, 442 pp.
Räsänen, M.E., Salo, J.S. and Kalliola, R.J. (1987). Fluvial perturbance in the western Amazon basin: regulation by long-term sub-Andean tectonics. *Science*, **238**, 1398–1401.
Räsänen, M.E., Salo, J.S., Jungner, H. and Pittmann, L.R. (1990). Evolution of the western Amazon lowland relief: impact of Andean foreland dynamics. *Terra Nova*, **2**, 320–332.
Rind, D. and Peteet, D. (1985). Terrestrial conditions at the Last Glacial Maximum and CLIMAP sea-surface temperature estimates: Are they consistent? *Quaternary Research*, **24**, 1–22.
Rodbell, D.T. (1992). Late Pleistocene equilibrium-line reconstructions in the northern Peruvian Andes. *Boreas*, **21**, 43–52.
Rodbell, D.T., Hansen, B.C.S. and Birkeland, P.W. (1991). The last glaciation and the nature of the last glacial–interglacial transition in the northern Peruvian Andes. *Abstracts, XIII INQUA Congress*, Beijing, China, 2–9 August 1991, p. 307.
Salo, J. (1987). Pleistocene forest refuges in the Amazon: evaluation of the biostratigraphical, lithostratigraphical and geomorphological data. *Ann. Zool. Fennici*, **24**, 203–211.
Schubert, C. and Clapperton, C.M. (1990). Quaternary glaciations in the northern Andes (Venezuela, Colombia and Ecuador). *Quaternary Science Reviews*, **9**, 123–135.
Seltzer, G.O. (1990). Recent glacial history and paleoclimate of the Peruvian–Bolivian Andes. *Quaternary Science Reviews*, **9**, 137–152.
Seltzer, G.O. (1992). Late Quaternary glaciation of the Cordillera Real, Bolivia. *Journal of Quaternary Science*, **7**, 87–98.
Semmel, A. (1985). Böden des feuchttropischen Afrikas und Fragen ihrer klimatischen Interpretation. *Geomethodica (Veröff. 10. B.G.C.)*, **10**, 71–89.
Sombroek, W.G. (1984). Soils of the Amazon region. *In*: Sioli, H. (ed.), *The Amazon. Limnology and Landscape Ecology of a Mighty Tropical River and its Basin*, pp. 521–535. W. Junk, Dordrecht.
van der Hammen, T., Duivenvoorden, J.F., Lips, J.M., Urrego, L.E. and Espejo, N. (1992a). Late Quaternary of the middle Caquetá River area (Colombian Amazonia). *Journal of Quaternary Science*, **7**, 45–55.
van der Hammen, T., Urrego, L.E., Espejo, N., Duivenvoorden, J.F. and Lips, J.M. (1992b). Late-glacial and Holocene sedimentation and fluctuations of river water level in the Caquetá River area (Colombian Amazonia). *Journal of Quaternary Science*, **7**, 57–67.
Van der Wijk, A., Elö-Daoushy, F., Arends, A.R. and Mook, W.G. (1986). Dating peat with U/Th disequilibrium: some geochemical considerations. *Chemical Geology (Isotope Geoscience Section)*, **59**, 283–292.
Vaz, J.E. and García-Miragaya, J. (1992). Thermoluminescence dating and chemistry of Quaternary sodic alluvial soils in the Venezuelan Savanna. *Catena*, **19**, 209–220.
Vogel, J.C. and Kronfeld, J. (1980). A new method for dating peat. *South African Journal of Science* **76**, 557–558.